Gauge-Higgs fits at the LHC

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Outline

Precise study of the SM particle interactions as a door for hints of New Physics.

Higgs coupling measurements

- Run I: SM hypothesis works, coupling strengths $\lesssim 20\%$.
- BSM: extended Higgs sectors, 2HDM, Higgs Portals, vector triplets, strongly sectors etc
- The Δ framework and beyond: **EFT**'s

Triple gauge boson couplings (WWV)

- SM: fixed by gauge invariance and renormalizability
- BSM: strong sectors (composite fermions/Higgs 1406.7320), new bosonic states (1510.03114), extra dimensional Gauge-Higgs unification (1604.01531).
- LHC (Run I) “combination”

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Why is a combined Gauge-Higgs analysis interesting?

Outline

◇ Δ-framework for Higgs interactions.

Simplest (yet powerful) framework: extended Higgs sector, Higgs portals, 2HDM.

T. Corbett, O. J. P. Éboli, D. Gonçalves, J. G–F, T. Plehn, M. Rauch, arXiv: 1505.05516

◇ Effective Lagrangian approach (linear).

The role of kinematic distributions, Off-shell measurements,
The role of correlations (Higgs –TGV)
The Higgs portal extension

A. Butter, T. Corbett, O. J. P. Éboli, D. Gonçalves, J. G–F, M. C. Gonzalez–Garcia, T. Plehn, M. Rauch,
arXiv: 1207.1344, 1211.4580, 1304.1151, 1505.05516, 1604.03105, 1607.04562

◇ Non-linear EFT.

Decorrelating Higgs – TGV

I. Brivio, T. Corbett, O. J. P. Éboli, M. B. Gavela, J. G–F, M. C. Gonzalez–Garcia, L. Merlo, S. Rigolin, J. Yepes,
arXiv: 1311.1823, 1406.6367, 1511.08188, 1604.06801

SFITTER

- Higgs analyses based on Run I event rates (159 measurements):

Modes	ATLAS	CMS
$H \to WW$	1412.2641	1312.1129
$H \to ZZ$	1408.5191	1312.5353
$H \to \gamma\gamma$	1408.7084	1407.0558
$H \to \tau\bar{\tau}$	1501.04943	1401.5041
$H \to b\bar{b}$	1409.6212	1310.3687
$H \to Z\gamma$	ATLAS-CONF-2013-009	1307.5515
$H \to$ invisible	1402.3244, ATLAS-CONF-2015-004	1404.1344
	1502.01518, 1504.04324,	CMS-PAS-HIG-14-038
$t\bar{t}H$ production	1408.7084,1409.3122	1407.0558,1408.1682
		1502.02485
kinematic distributions	1409.6212,1407.4222	
off-shell rate	ATLAS-COM-CONF-2014-052	1405.3455

- Correlated experimental uncertainties
- Default: Box shaped theoretical uncertainties
- Default: Uncorrelated production theoretical uncertainties

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◇ NMSSM-DM: Butter, Plehn, Rauch, Zerwas, Henrot-Versillé, Lafaye in 1507.02288

◇ MSSM-DM: Henrot-Versillé, Lafaye, Plehn, Rauch, Zerwas, Plaszczynski, Rouillé d'Orfeuil, Spinelli in 1309.6958

Δ–framework: rate–based analysis

Study the Higgs interactions using as a parametrization the SM operators with free couplings:

$$
\begin{aligned}
g_x &= g_x^{\text{SM}}\ (1+\Delta_x) \\
g_\gamma &= g_\gamma^{\text{SM}}\ (1+\Delta_\gamma^{\text{SM}}+\Delta_\gamma) \equiv g_\gamma^{\text{SM}}\ (1+\Delta_\gamma^{\text{SM+NP}}) \\
g_g &= g_g^{\text{SM}}\ (1+\Delta_g^{\text{SM}}+\Delta_g) \equiv g_g^{\text{SM}}\ (1+\Delta_g^{\text{SM+NP}})\ ,
\end{aligned}
$$

Thus, the Lagrangian is:

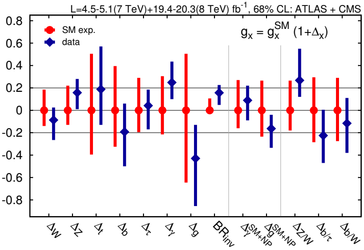
$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\text{SM}} &+ \Delta_W\ g m_W H\ W^\mu W_\mu + \Delta_Z\ \frac{g}{2c_w} m_Z H\ Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f\ \frac{m_f}{v} H\left(\bar{f}_R f_L + \text{h.c.}\right) \\
&+ \Delta_g F_G\ \frac{H}{v}\ G_{\mu\nu}G^{\mu\nu} + \Delta_\gamma F_A\ \frac{H}{v}\ A_{\mu\nu}A^{\mu\nu} + \text{invisible decays}\ ,
\end{aligned}
$$

Can be linked to extended Higgs sectors, 2HDM, Higgs Portals etc → see Lopez–Val *et al* 1308.1979

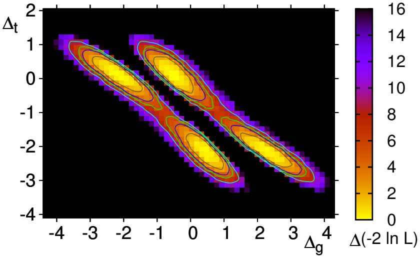
Can also be linked to the non–linear Effective Lagrangian → see for instance Buchalla *et al* 1504.01707

Δ–framework: results

◇ 68% CL error bars:



◇ Well understood correlations:



◇ Extended Higgs sectors, *e. g.* extra Singlet:

$\cos\alpha = 1 + \Delta_H \in [0.93, 1.]$ at 68% CL.

◇ Simple 2HDM, Composite Higgs:

$\Delta_V \in 6\%$ and $\Delta_f \in 12\%$ at 68% CL.

◇ Higgs Portals:

$\text{BR}_{\text{inv}} < 30.6\%$ at 95% CL.

More details *e. g.* Lopez–Val *et al* 1308.1979

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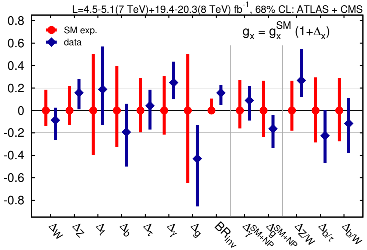

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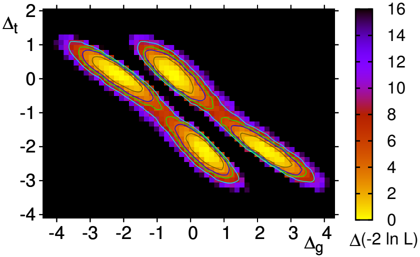

◇ Everything consistent with the SM.

◇ Δ–framework is well aligned with experimental measurements. Suitable for testing different analysis details→ **1505.05516**

Correlated theory uncertainties, Gaussian vrs flat, N^3LO for gluon fusion ...

◇ Δ–framework only suitable for rate–based analysis, and only for Higgs interactions.

How to add information from kinematic distributions? EWSB sector?→ Effective Lagrangian!

Effective Lagrangian Approach

$\sim O(30)$ years: SM success motivates model independent parametrization for NP $\to \mathcal{L}_{\rm eff}$

Key principle: To describe physics at some scale (for us, LHC), we do not need to know all the details of the dynamics at a much higher scale.

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_{m=1}^{\infty} \sum_n \frac{f_n^{(4+m)}}{\Lambda^m} \mathcal{O}_n^{(4+m)}$$

Based on symmetries and particle content at low energy.

Model Independent: Captures (almost) any NP BSM without committing to a specific BSM extension. If no NP appears quantify the exclusion accuracy on NP.
Provides an **ordering** principle in terms of Λ.

First flavor, then LEP/2 and EWPD, TGV, also Higgs at LEP and Tevatron

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Apply it to the Higgs sector!

1207.1344

Effective Lagrangian: the linear realization

Bottom-up model-independent effective Lagrangian approach:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0^{\rm SM} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

Particle content ($SU(2)_L$ doublet), Symmetries (SM, lepton, baryon, CP)

[1] $D_\mu \Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W_\mu^a\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

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Choice of basis: EOM, huge variety of data **(DATA–DRIVEN)**, focus measurable at LHC:

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$$\begin{array}{lll}
\mathcal{O}_{GG} = \Phi^\dagger\Phi\; G^a_{\mu\nu}G^{a\mu\nu}, & \mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi, & \mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi, \\
\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right), & \mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi), & \mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi), \\
\mathcal{O}_{e\Phi,33} = (\Phi^\dagger\Phi)(\bar{L}_3\Phi e_{R,3}), & \mathcal{O}_{u\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\tilde{\Phi}u_{R,3}), & \mathcal{O}_{d\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_3\Phi d_{R,3})\;, \\
\mathcal{O}_{WWW} = {\rm Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^\mu\right) & &
\end{array}$$

Thus, 10 parameters for Gauge-Higgs sector:

$$\frac{f_{GG}}{\Lambda^2}, \frac{f_{WW}}{\Lambda^2}, \frac{f_{BB}}{\Lambda^2}, \frac{f_{\phi,2}}{\Lambda^2}, \frac{f_W}{\Lambda^2}, \frac{f_B}{\Lambda^2}, \frac{f_\tau}{\Lambda^2}, \frac{f_b}{\Lambda^2}, \frac{f_t}{\Lambda^2}, \frac{f_{WWW}}{\Lambda^2}$$

[1] $D_\mu\Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W^a_\mu\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

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Let's see them in unitary gauge

[1] $D_\mu\Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W^a_\mu\right)\Phi$, $\hat{B}_{\mu\nu} = i\frac{g'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu}$

Effective Lagrangian for Higgs Interactions

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_{\mu}Z^{\mu} \\
&+ +g^{(1)}_{HWW}\left(W^{+}_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\; HW^{+}_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^{+}_{\mu}W^{-\,\mu}
\end{aligned}
$$

$$
\mathcal{L}_{\rm eff}^{Hff} = g^{f}_{Hij}\bar{f}_L f_R H + \text{h.c.}
$$

$$
\begin{aligned}
g_{Hgg} &= -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} &&, g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \;, \\
g^{(1)}_{HZ\gamma} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} &&, g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \;, \\
g^{(1)}_{HZZ} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} &&, g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \;, \\
g^{(1)}_{HWW} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} &&, g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW} \;, \\
g^{f}_{Hij} &= -\frac{m^f_i}{v}\left(1 - \frac{v^2}{\sqrt{2}\Lambda^2} f_f\right) &&, g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)
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$$
g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \; ,
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\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_\mu Z^\mu \\
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\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar f_L f_R H + \text{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2 vs^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2} \quad ,$$

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$$g^f_{Hij} = -\frac{m^f_i}{v}\left(1 - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right) \quad , g^{\Phi,2}_{Hxx} = g^{\rm SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

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Global analysis of the Higgs interactions I

Event rates (159) from ATLAS and CMS:

$H \to WW$
$H \to ZZ$
$H \to \gamma\gamma$
$H \to \tau\bar{\tau}$
$H \to b\bar{b}$
$H \to Z\gamma$
$H \to$ invisible
$t\bar{t}H$ production

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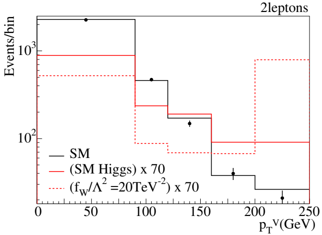
Distributions from ATLAS $H \to b\bar{b}$ (1409.6212):



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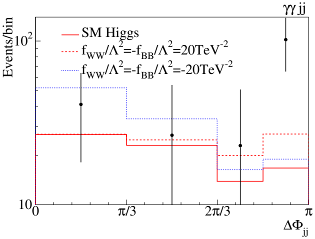
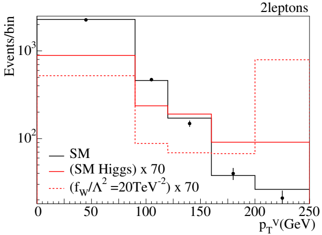


Distributions from ATLAS $H \to b\bar{b}$ (1409.6212):



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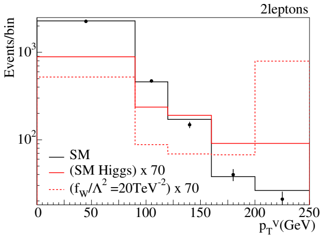

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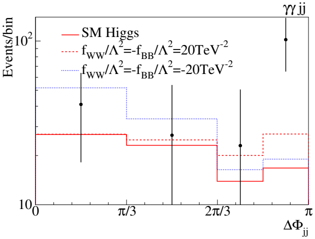
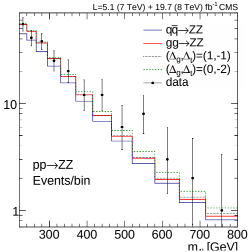
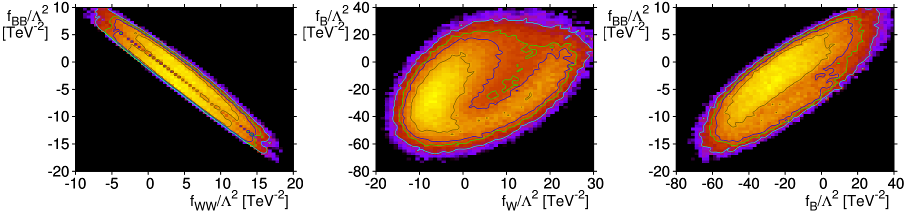


$m_{4\ell}$ from off–shell measurements:



Full dimension-6 analysis



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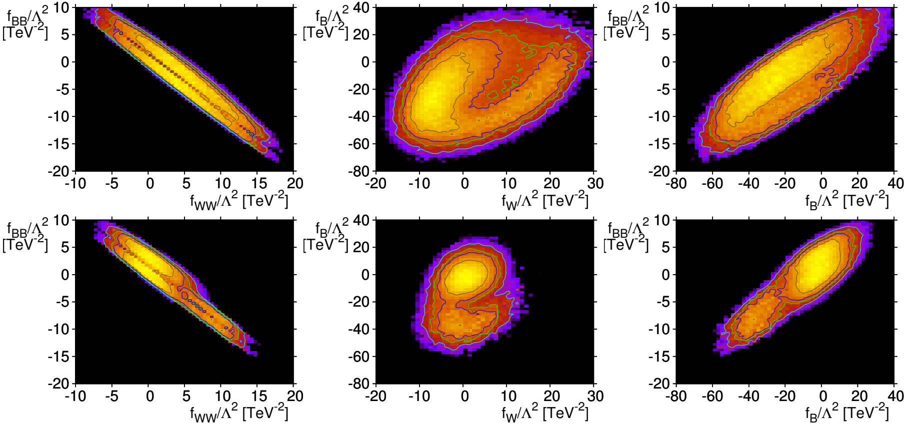

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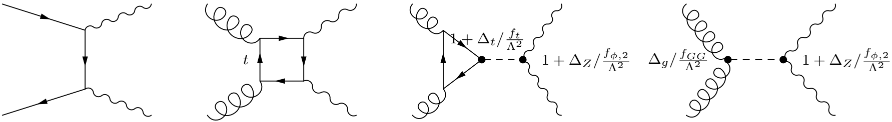

Continuum background $q\bar{q}\,(gg) \to ZZ$ (left) and Higgs signal $gg \to H \to ZZ$ (right).

$$\mathcal{M}_{gg\to ZZ} = (1+\Delta_Z)\left[(1+\Delta_t)\mathcal{M}_t + \Delta_g \mathcal{M}_g\right] + \mathcal{M}_c$$

$$\frac{d\sigma}{dm_{4\ell}} = (1+\Delta_Z)\left[(1+\Delta_t)\frac{d\sigma_{tc}}{dm_{4\ell}} + \Delta_g\frac{d\sigma_{gc}}{dm_{4\ell}}\right] + (1+\Delta_Z)^2\left[(1+\Delta_t)^2\frac{d\sigma_{tt}}{dm_{4\ell}} + (1+\Delta_t)\Delta_g\frac{d\sigma_{tg}}{dm_{4\ell}} + \Delta_g^2\frac{d\sigma_{gg}}{dm_{4\ell}}\right] + \frac{d\sigma_c}{dm_{4\ell}}\ .$$

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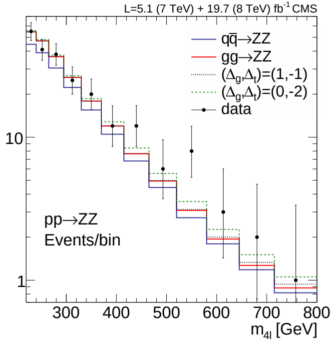
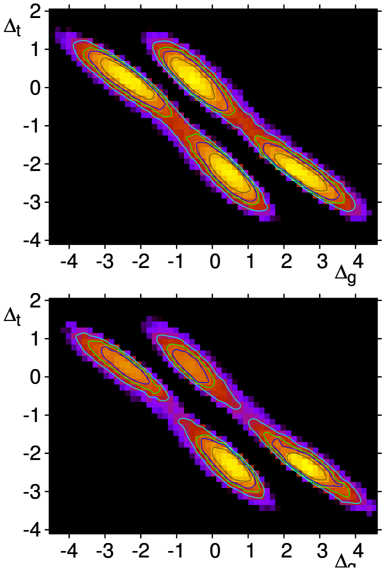


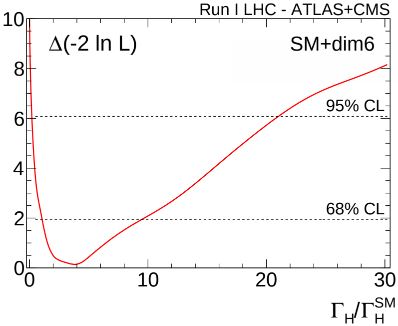


- Here we can use ATLAS and CMS
- Bins directly into the analysis

Γ_H from off–shell measurements

$$\sigma^{\text{on-shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H)\, g_f^2(m_H)}{\Gamma_H} \qquad \text{vrs.} \qquad \sigma^{\text{off-shell}}_{i\to H^*\to f} \propto g_i^2(m_{4\ell})\, g_f^2(m_{4\ell}) \quad .$$

- $\Gamma_H < 9.3\Gamma_H^{SM}$ 68% CL
- May allow to bound the Higgs total decay width under certain assumptions.
- Here including effective operators (and not only the gluon fusion top-loop induced production).



$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W\, g m_W H\, W^\mu W_\mu + \Delta_Z\, \frac{g}{2c_w} m_Z H\, Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f\, \frac{m_f}{v} H\,(\bar{f}_R f_L + \text{h.c.})$$

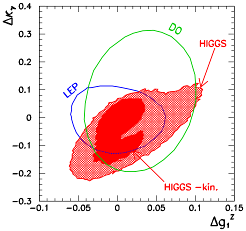
$$+ \Delta_g F_G\, \frac{H}{v}\, G_{\mu\nu}G^{\mu\nu} + \Delta_\gamma F_A\, \frac{H}{v}\, A_{\mu\nu}A^{\mu\nu} + \text{invisible decays} + \text{unobservable decays}\ .$$

Effective Lagrangian for TGV interactions

The usual Lagrangian to study TGV interactions since LEP:

$$\mathcal{L}_{\text{eff}}^{WWV} = g_{WWV}\Bigg(- i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu W^{\mu\nu} V_\nu \right) - i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} - i \frac{\lambda_V}{M_W^2} W^\dagger_{\rho\mu} W^\mu_\nu V^{\nu\rho} \Bigg)$$

These can be directly measured at Colliders in diboson production ($WW, WZ, W\gamma$):



$$\begin{aligned}
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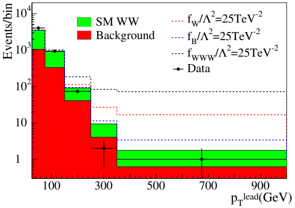

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Analysis Framework

arXiv:1604.03105

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- Statistical analysis: **SFITTER**

Log-likelihood analysis: statistical, background, systematic, and theory uncertainties.
Including correlations

Validation: example ATLAS WW at 8TeV

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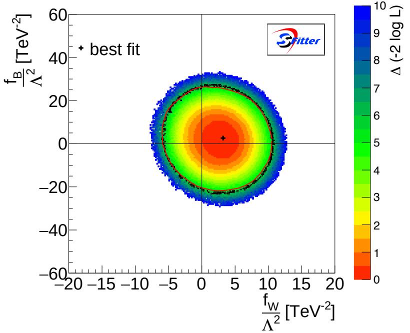

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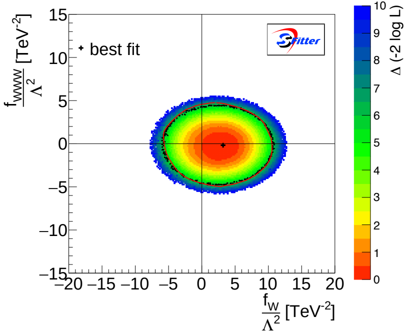
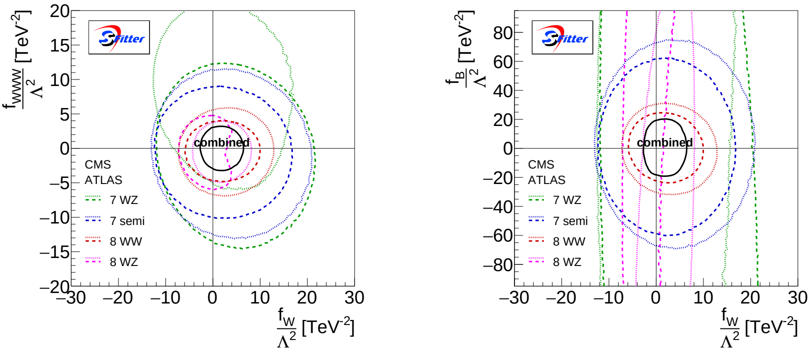


Combined LHC Run I results

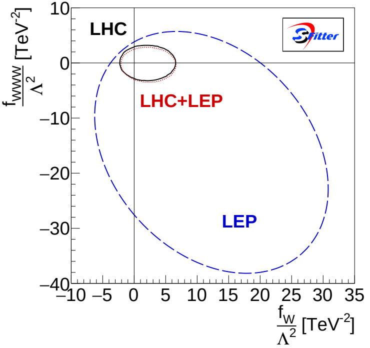
arXiv:1604.03105

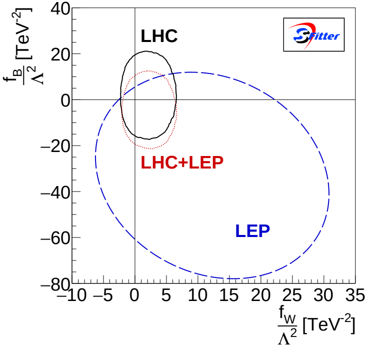


Variety of channels leads to strong constraints:

- ◇ Strongest: f_{WWW}/Λ^2 (from WW and WZ), close: f_W/Λ^2 (also from both).
- ◇ f_B weaker: only WW (in WWZ $\frac{s_w^2}{c_w^2}$ suppression).
- ◇ Semileptonic 8 TeV would improve the results.

Comparison and combination with LEP arXiv:1604.03105





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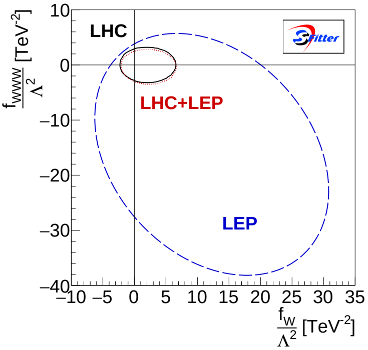
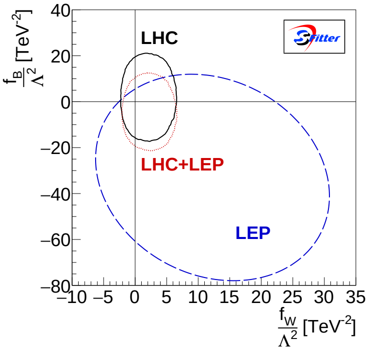




- ◇ LHC+LEP 95%CL (1-dim profiled)

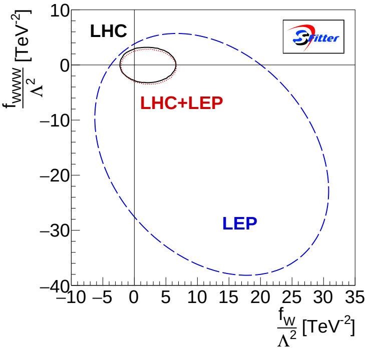
$$\frac{f_W}{\Lambda^2} \in [-1.3,\ 6.3]\ \text{TeV}^{-2} \quad , \frac{f_B}{\Lambda^2} \in [-18, 5,\ 10.9]\ \text{TeV}^{-2} \quad , \frac{f_{WWW}}{\Lambda^2} \in [-2.7,\ 2.8]\ \text{TeV}^{-2}\ .$$

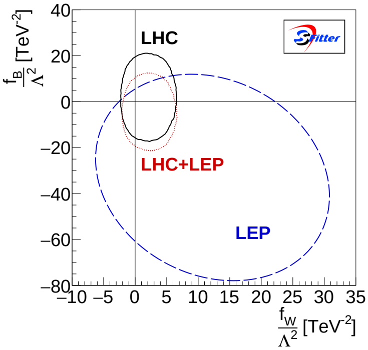
- ◇ LHC 95% CL (1-dim profiled)

$$\Delta g_1^Z \in [-0.006,\ 0.026] \quad , \Delta\kappa_\gamma \in [-0.041,\ 0.072] \quad , \lambda_{\gamma,Z} \in [-0.0098,\ 0.013]\ .$$

Comparison and combination with LEP

arXiv:1604.03105

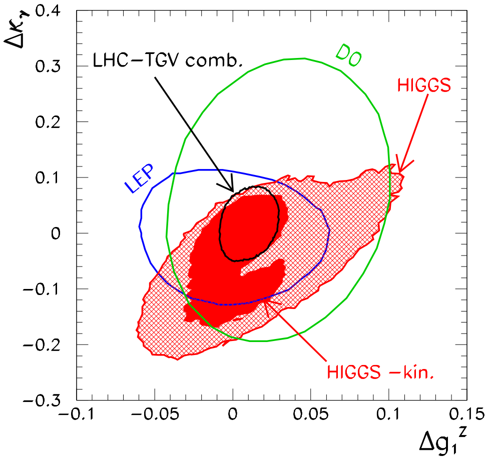




	LHC Run I			
	68 % CL	Correlations		
Δg_1^Z	0.010 ± 0.008	1.00	0.19	-0.06
$\Delta\kappa_\gamma$	0.017 ± 0.028	0.19	1.00	-0.01
λ	0.0029 ± 0.0057	-0.06	-0.01	1.00

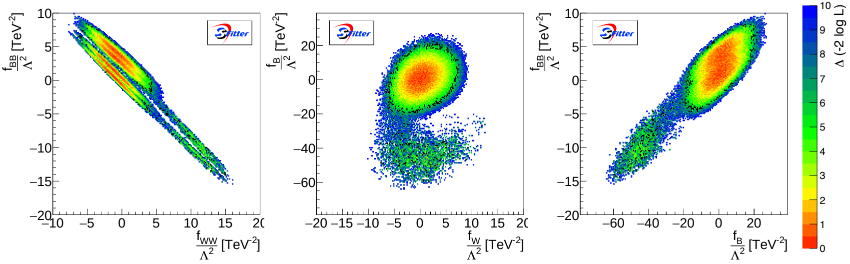
Combined Gauge-Higgs results

arXiv:1604.03105



Combined Gauge-Higgs results

arXiv:1505.05516



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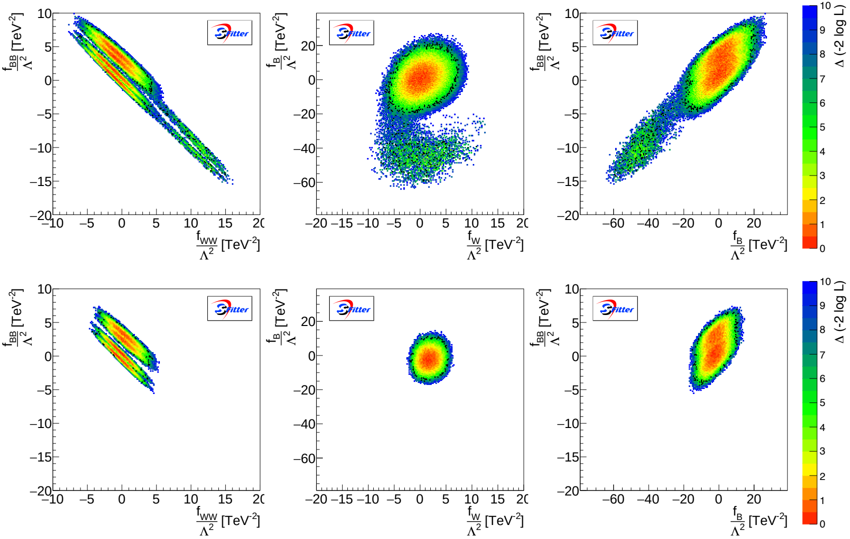
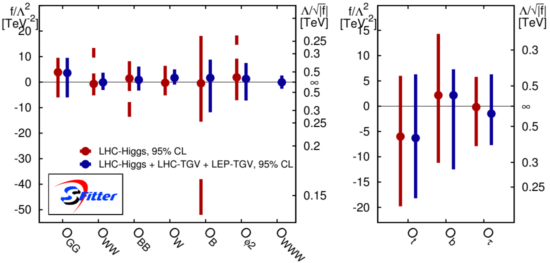
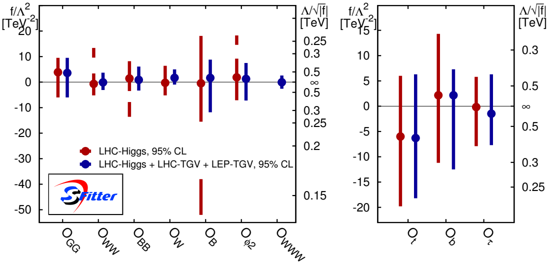


EFT expansion?



With the current sensitivity, this is model dependent dimension–6 Lagrangian.

EFT expansion?



With the current sensitivity, this is model dependent dimension–6 Lagrangian.

EFT vrs. full model: Biekoetter *et al* 1406.7320, Gorbhan *et al* 1502.07352, Dawson *et al* 1501.04103, Craig *et al* 1411.0676, Drozd *et al* 1504.02409, Brehmer *et al* **1510.03443** and 1607.08251, Contino *et al* 1604.06444, Falkowski *et al* 1609.06312, Zhang 1610.01618 etc.

- Several weakly interacting extensions: extra singlet, extra doublet, vector triplet, colored scalar partner
- Several Higgs channels: Associated production, WBF, decays to photons, 4ℓ, hh
- Several variables: $m_{4\ell}, m_{VH}, p_{T,j}, \Delta\Phi_{jj}$ etc

Interesting questions arise about how to perform the matching.

Disentangling a dynamical Higgs

- Motivated by composite models $\rightarrow$ Higgs as a PGB of a global symmetry.
- Non-linear or "chiral" effective Lagrangian expansion including the light Higgs.

SM Gauge bosons and fermions

Light Higgs $\rightarrow$ without a given model treated as generic "singlet" h $F_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \ldots$	$\leftrightarrow$	h is not part of Φ More possible operators
Dimensionless unitary matrix: $\mathsf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$ $(\mathsf{V}_\mu \equiv (\mathsf{D}_\mu \mathsf{U})\,\mathsf{U}^\dagger$ and $\mathsf{T} \equiv \mathsf{U}\sigma_3\mathsf{U}^\dagger)$	$\leftrightarrow$	Relative reshuffling of the order at which operators appear

- The Lagrangian is now:

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta\mathcal{L}$$

Comparison with the linear basis!

The Non-linear Lagrangian

Alonso *et al* 1212.3305
Brivio *et al* 1604.06801
Buchalla *et al* 1307.5017

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta\mathcal{L}$$

Leading order Lagrangian[2]

$$\begin{aligned}\mathcal{L}_0 \quad = \quad & \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - V(h) \\ & -\frac{v^2}{4}\mathrm{Tr}[\mathsf{V}_\mu\mathsf{V}^\mu]\mathcal{F}_C(h) + i\bar{Q}\not{D}Q + i\bar{L}\not{D}L \\ & -\frac{v}{\sqrt{2}}\left(\bar{Q}_L\mathsf{U}\mathbf{Y}_Q(h)Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\bar{L}_L\mathsf{U}\mathsf{Y}_L L_R + \mathrm{h.c.}\right) \,,\end{aligned}$$

Next order: $\Delta\mathcal{L} = \Delta\mathcal{L}_{\text{bos}} + \Delta\mathcal{L}_{\text{fer}}$. For instance, bosonic CP-even part:

$$\begin{aligned}\Delta\mathcal{L}^{CP}_{\text{bos}} \quad = \quad & c_B\mathcal{P}_B(h) + c_W\mathcal{P}_W(h) + c_G\mathcal{P}_G(h) + c_T\mathcal{P}_T(h) \\ + \quad & c_{DH}\mathcal{P}_{DH}(h) + \sum_{1-6,8} c_i\mathcal{P}_i(h) + \sum_{11-14} c_i\mathcal{P}_i(h) \\ + \quad & \sum_{17,18,20} c_i\mathcal{P}_i(h) + \sum_{20-24,26} c_i\mathcal{P}_i(h) + \sum_{WWW,GGG} c_i\mathcal{P}_i(h)\end{aligned}$$

[2] $\mathsf{D}_\mu\mathsf{U}(x) \equiv \partial_\mu\mathsf{U}(x) + igW_\mu(x)\mathsf{U}(x) - \frac{ig'}{2}B_\mu(x)\mathsf{U}(x)\sigma_3 \quad , \qquad \mathbf{Y}_{Q,L} \equiv \mathbf{diag}\left(Y_{U,\nu},\, Y_{D,L}\right)$

The Non-linear Lagrangian

Alonso *et al* 1212.3305
Brivio *et al* 1604.06801

$$-\frac{v^2}{4}\mathrm{Tr}[\mathsf{V}_\mu \mathsf{V}^\mu]\mathcal{F}_C(h)$$

$$\mathcal{P}_T(h) = \frac{v^2}{4}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_T(h)$$

$$\mathcal{P}_B(h) = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B$$

$$\mathcal{P}_W(h) = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W$$

$$\mathcal{P}_G(h) = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G$$

$$\mathcal{P}_{DH}(h) = \left(\partial_\mu \mathcal{F}_{DH}(h)\partial^\mu \mathcal{F}'_{DH}(h)\right)^2$$

$$\mathcal{P}_1(h) = B_{\mu\nu}\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1$$

$$\mathcal{P}_2(h) = \frac{i}{4\pi}B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2$$

$$\mathcal{P}_3(h) = \frac{i}{4\pi}\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3$$

$$\mathcal{P}_4(h) = \frac{i}{4\pi}B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4$$

$$\mathcal{P}_5(h) = \frac{i}{4\pi}\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5$$

$$\mathcal{P}_6(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6$$

$$\mathcal{P}_8(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\partial^\mu\mathcal{F}_8\partial^\nu\mathcal{F}'_8$$

$$\mathcal{P}_{11}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}$$

$$\mathcal{P}_{12}(h) = (\mathrm{Tr}(\mathbf{T}W_{\mu\nu}))^2\mathcal{F}_{12}$$

$$\mathcal{P}_{13}(h) = \frac{i}{4\pi}\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_{13}$$

$$\mathcal{P}_{14}(h) = \frac{\varepsilon^{\mu\nu\rho\lambda}}{4\pi}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}$$

$$\mathcal{P}_{17}(h) = \frac{i}{4\pi}\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}$$

$$\mathcal{P}_{18}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}$$

$$\mathcal{P}_{20}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\mathcal{F}_{20}\partial^\nu\mathcal{F}'_{20}$$

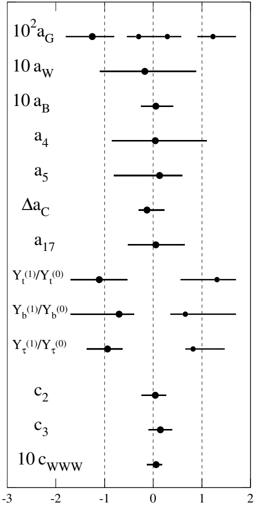
$$\mathcal{P}_{21}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\mathcal{F}_{21}\partial^\nu\mathcal{F}'_{21}$$

And $\mathcal{P}_{22}(h),\ \mathcal{P}_{23}(h),\ \mathcal{P}_{24}(h),\ \mathcal{P}_{26}(h)$.

Analysis using only Higgs data

Brivio *et al* 1604.06801

Focusing on Higgs trilinear interactions not many changes:



Decorrelating Higgs and TGV

Interesting aspects show up when comparing different measurements

[3] Parallel reasoning applies to $\mathcal{O}_W$ and $\mathcal{P}_3 - \mathcal{P}_5$

Decorrelating Higgs and TGV

Interesting aspects show up when comparing different measurements:

In the linear case[3]

$$\left.\begin{aligned}\mathcal{O}_B \quad = \quad & \frac{ieg^2}{8}A_{\mu\nu}W^{-\mu}W^{+\nu}(v+h)^2 - \frac{ie^2 g}{8\cos\theta_W}Z_{\mu\nu}W^{-\mu}W^{+\nu}(v+h)^2 \\ & -\frac{eg}{4\cos\theta_W}A_{\mu\nu}Z^{\mu}\partial^{\nu}h(v+h) + \frac{e^2}{4\cos^2\theta_W}Z_{\mu\nu}Z^{\mu}\partial^{\nu}h(v+h)\end{aligned}\right\} \text{Higgs-TGV Correlated!}$$

whereas in the non-linear case

$$\left.\begin{aligned}\mathcal{P}_2(h) \quad &= \quad 2ieg^2 A_{\mu\nu}W^{-\mu}W^{+\nu}\mathcal{F}_2(h) - 2\frac{ie^2 g}{\cos\theta_W}Z_{\mu\nu}W^{-\mu}W^{+\nu}\mathcal{F}_2(h) \\ \mathcal{P}_4(h) \quad &= \quad -\frac{eg}{\cos\theta_W}A_{\mu\nu}Z^{\mu}\partial^{\nu}\mathcal{F}_4(h) + \frac{e^2}{\cos^2\theta_W}Z_{\mu\nu}Z^{\mu}\partial^{\nu}\mathcal{F}_4(h)\end{aligned}\right\} \text{Higgs-TGV may be decorrelated!}$$

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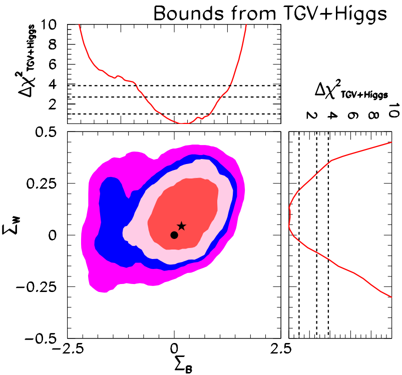
Perform global Higgs-TGV analysis, with non-linear coefficients, defining:

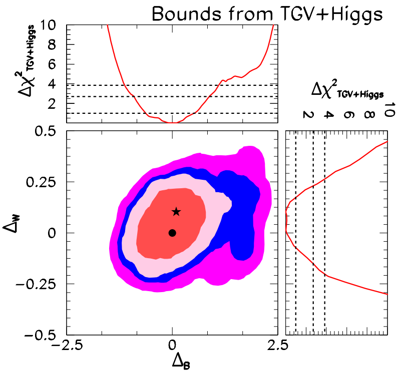
$$\Sigma_B \equiv 4(2c_2 + a_4)\,, \qquad \Sigma_W \equiv 2(2c_3 - a_5)\,,$$
$$\Delta_B \equiv 4(2c_2 - a_4)\,, \qquad \Delta_W \equiv 2(2c_3 + a_5)\,,$$

order $d = 6$ of the linear regime $\Sigma_B = \frac{f_B}{\Lambda^2}$, $\Sigma_W = \frac{f_W}{\Lambda^2}$, while $\Delta_B = \Delta_W = 0$.

[3] Parallel reasoning applies to $\mathcal{O}_W$ and $\mathcal{P}_3 - \mathcal{P}_5$

Decorrelating Higgs and TGV





Left:A BSM sensor irrespective of the type of expansion: constraints from TGV and Higgs data on the combinations $\Sigma_B = 4(2c_2 + a_4)$ and $\Sigma_W = 2(2c_3 - a_5)$, which converge to c_B and c_W in the linear $d = 6$ limit.

Right:A non-linear versus linear discriminator: constraints on the combinations $\Delta_B = 4(2c_2 - a_4)$ and $\Delta_W = 2(2c_3 + a_5)$, which would take zero values in the linear (order $d = 6$) limit (as well as in the SM), indicated by the dot at $(0, 0)$.

Higher order differences

arxiv:1311.1823

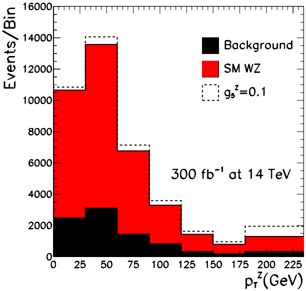
Reshuffling $\rightarrow$ interactions that are strongly suppressed in one case may be leading corrections in the other.

More on TGV!

- At *first* order in non-linear expansion (but at dim–8 in the linear one) $\mathcal{P}_{14}$ contributes to anomalous TGV: g_5^Z (C- and P-odd but CP even).

$$\mathcal{L}_{WWV} = -ig_5^V \, \epsilon^{\mu\nu\rho\sigma} \left(W_\mu^+ \partial_\rho W_\nu^- - W_\nu^- \partial_\rho W_\mu^+ \right) V_\sigma$$

$$\rightarrow -\xi^2 \, \frac{g^3}{\cos\theta_W} \, \varepsilon^{\mu\nu\rho\lambda} [p_{+\lambda} + p_{-\lambda}]$$



- Chiral expansion: several operators contribute to QGVs without inducing TGVs $\rightarrow$ coefficients less constrained at present (larger deviations may be expected). Linear expansion: modifications of QGVs that do not induce changes to TGVs appear only when $d = 8$.

Summary

- **Higgs**:

  ◇ Δ–framework: well aligned with experimental measurements.

  ◇ EFT: **Kinematic distributions** included, key feature.

- **Gauge-Higgs**:

  ◇ Combination of LHC Run I EW pair production: improves LEP TGV bounds.

  ◇ (De)correlations Higgs–TGV $\rightarrow$ dinsentangling Higgs nature.

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Thank you!